X-56A Flight-test Approach for Envelope Expansion Past Open-loop Flutter Instability

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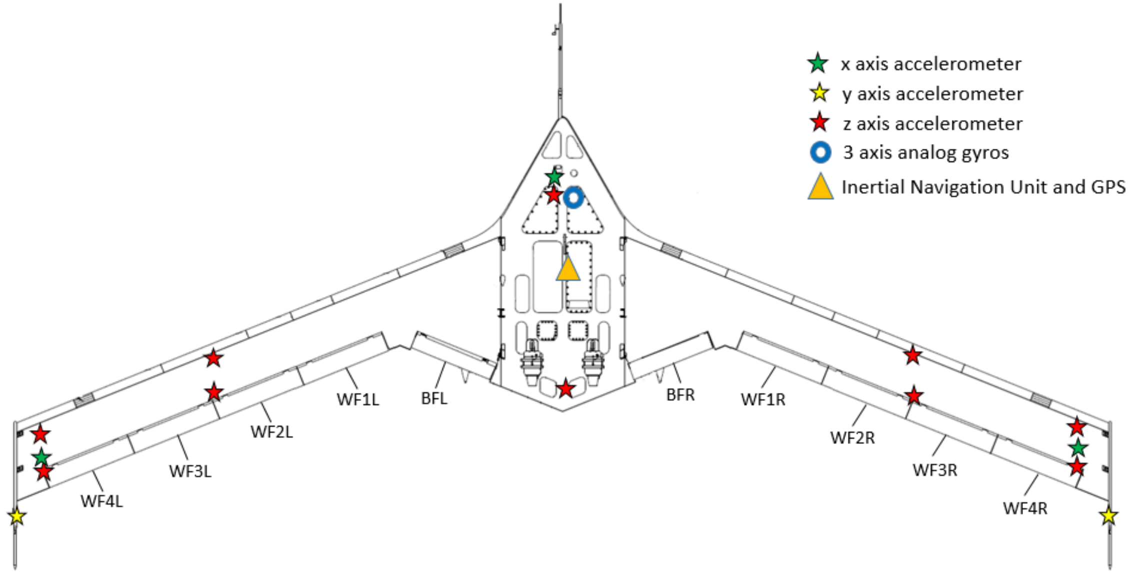
X-56A Project Background

- Problem: Contemporary aircraft carry around structural mass so that the flutter instabilities lie well outside of the operational envelope.
- X-56A Research Goal: advance the state of the art in modeling and control technologies to enable highly optimized lighter weight aircraft designs with less margin from flutter
- Testing aircraft with flutter instabilities within their operational flight envelope is inherently high-risk
  - Very little validation data to anchor preflight predictions
  - Instabilities give very little warning before reaching destructive levels
- The X-56A aircraft were remotely piloted and relatively inexpensive to enable executing such an inherently high-risk flight-test program.
- The aircraft constructed in such a way that they were realistic testbeds for the relevant physics applicable to full scale aircraft.

System Descriptions - Aircraft

- Vehicle Specs. and configuration
  - 28-ft wingspan;
  - a maximum takeoff weight of 550 lb;
  - 10 trailing-edge control surfaces;
  - fixed vertical winglets;
  - fixed tricycle-configuration landing gear.
  - a ballistic recovery parachute system which could be triggered as part of the flight termination system (FTS).
  - powerplant - two JetCat P-400 engines
- Vehicle construction:
  - Centerbody constructed from carbon fiber composites with honeycomb bulkheads.
  - Conventional wing design with fore and aft wing spars, and ribs constructed from carbon fiber.
  - Carbon fiber skins on the stiff wings
  - Fiberglass skins on flexible wings



System Descriptions – GCS and Simulation

- One facility – 3 integrated functions (Cockpit, mission control center, simulation)
  - Integrating functions and co-locating the flight crew and discipline engineers key to efficiency, communication and situational awareness, and crew resource management
- Cockpit (Pilot and Co-pilot stations)
  - Bi-directional C2 link
  - Side stick, rudder pedals, and dual throttles
  - Out-the-nose video with HUD overlay
  - External cameras and moving maps
  - Critical vehicle information including engine, fuel, and battery data
  - Research system interfaces
  - Warnings, cautions, and emergency mode activation
- Mission Control Room
  - Engineers monitor real-time telemetry data from the aircraft monitoring flight safety and mission success
  - Key roles: mission controller, flight controls, structures, flight systems, principal investigator, project management
- Pilot in the loop simulation
  - Non-linear piloted simulation interfaced with the same cockpit hardware, software, and displays used for the flight configuration
  - Capability to drive real-time data displays for the discipline engineer stations.
  - Facilitated realistic mission rehearsals and pilot and mission control training.

X-56A Flight Test Brief Overview

- Flight test program included a total of 54 flights across the two vehicles and 31 flights in the flexible wing configuration

Flights
X Accidents

		2013	2014	2015	2016	2017	2018	2019
CB #1 (LM)	Stiff Wings							
	Flex Wings			X Loss of Vehicle				

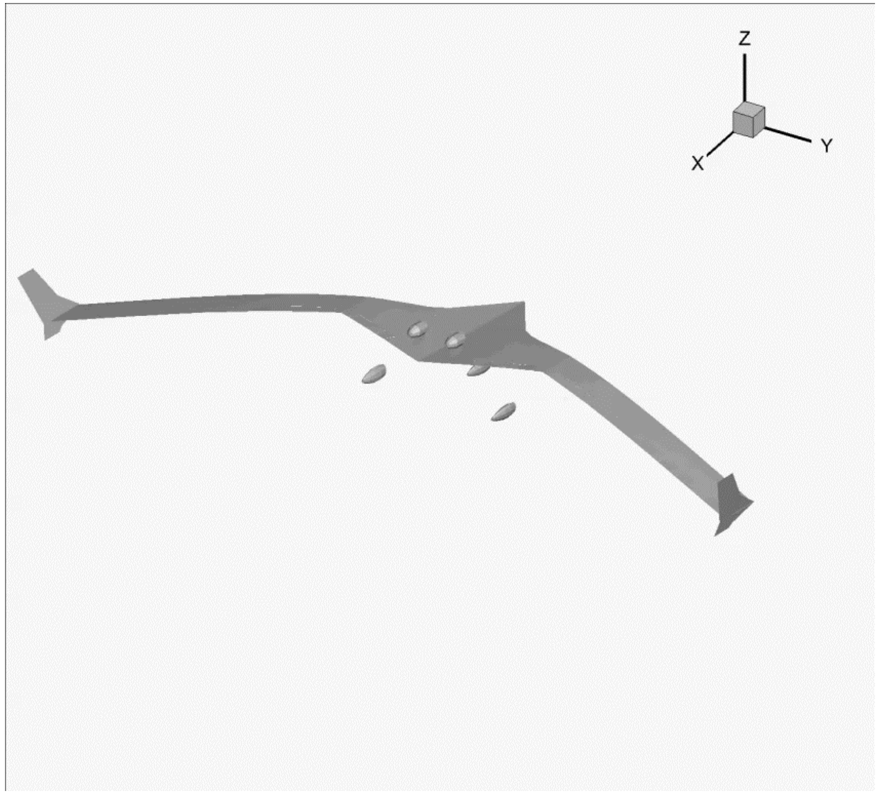
		2013	2014	2015	2016	2017	2018	2019
CB #2 (NASA)	Stiff Wings			X Repairable				
	Flex Wings							
	X-56B Wings							

Takeoff and Landing Challenges

- Landing
  - Factors that make landing the X-56A challenging
    - No horizontal tail and aft main landing gear result in uncontrolled de-rotation on touch down
    - Stiff landing gear designed for parachute landing loads not normal landing loads
    - Flexible wings absorb energy on landing
    - Net result - less energy dissipated in the landing gear and more absorbed in the aircraft structure
  - NASA fixes prior to flexible-wing flights
    - Redesigned nose gear to absorb more energy
    - Updated simulation to include landing gear and aircraft structural coupling
    - Designed an active control mode for damping out nose bouncing
- Takeoff
  - Factors that create a situation on takeoff that can cause an uncontrollable pitch-up on takeoff
    - Aircraft configurable with a range of center of gravity locations including static instability.
    - Aircraft rotation challenges due to main landing gear aft of the aerodynamic center and lack of horizontal tail
    - Wing flexibility results in wings deflecting up on rotation and a pitch-up moment due to wing sweep.
  - NASA fixes prior to flexible-wing flights
    - Nose-high attitude on the ground to reduce the amount of rotation required on takeoff, and to reduce the lift transient.
    - Adverse effects: reduced ability for rejected takeoffs, residual lift on landing rollout
    - Hiking nose gear would have been ideal, too much weight and mechanical complexity

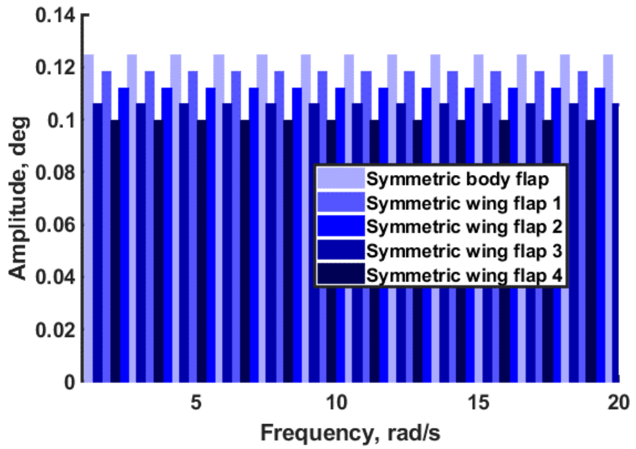
Flutter Envelope Expansion

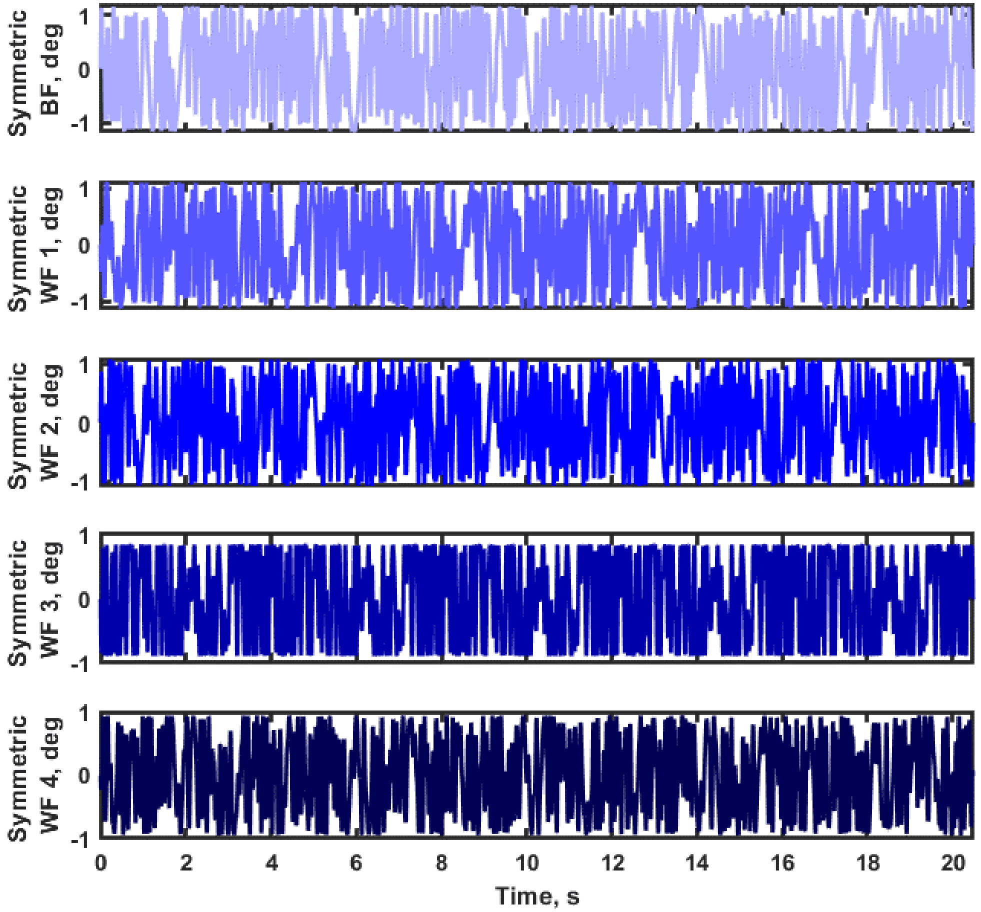
- Flight above the flutter speed is inherently risky
  - Explosive nature of flutter instabilities
  - Modeling uncertainty
  - Lack of data to validate preflight predictions.
- Unconventional X-56A flutter mechanism
  - Coupling of the short-period and first wing bending modes
  - Most flutter mechanisms only involve structural modes which simplifies the modeling problem
  - Critical flight condition: High speed, forward cg (low fuel)
- Flight-test approach
  - Specialized flight test maneuvers
  - Cautious build-up approach with real-time monitoring of control law margin and performance, and coupled dynamics
  - Post-flight data analysis to validate and update preflight models and designs based on flight data



Maneuvers and Real-time Monitoring

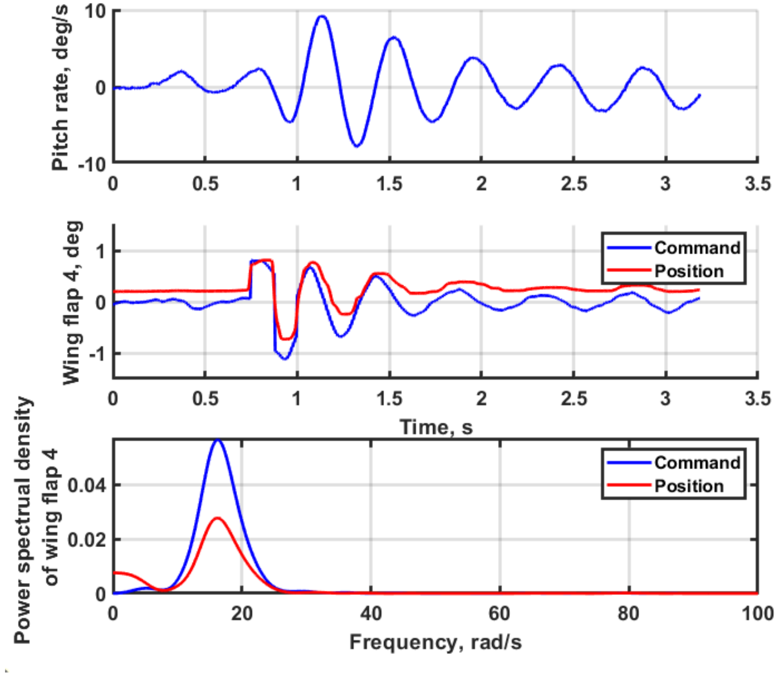
- Integrated test block at each new flight condition
  - Frequency-tuned surface rap to enable the assessment of modal damping and system stability
  - Pilot pitch and roll captures to assess piloted flying qualities
  - Multisine maneuvers for post-flight control-loop margin assessments
  - Multisine maneuvers for post-flight parameter estimation and model tuning





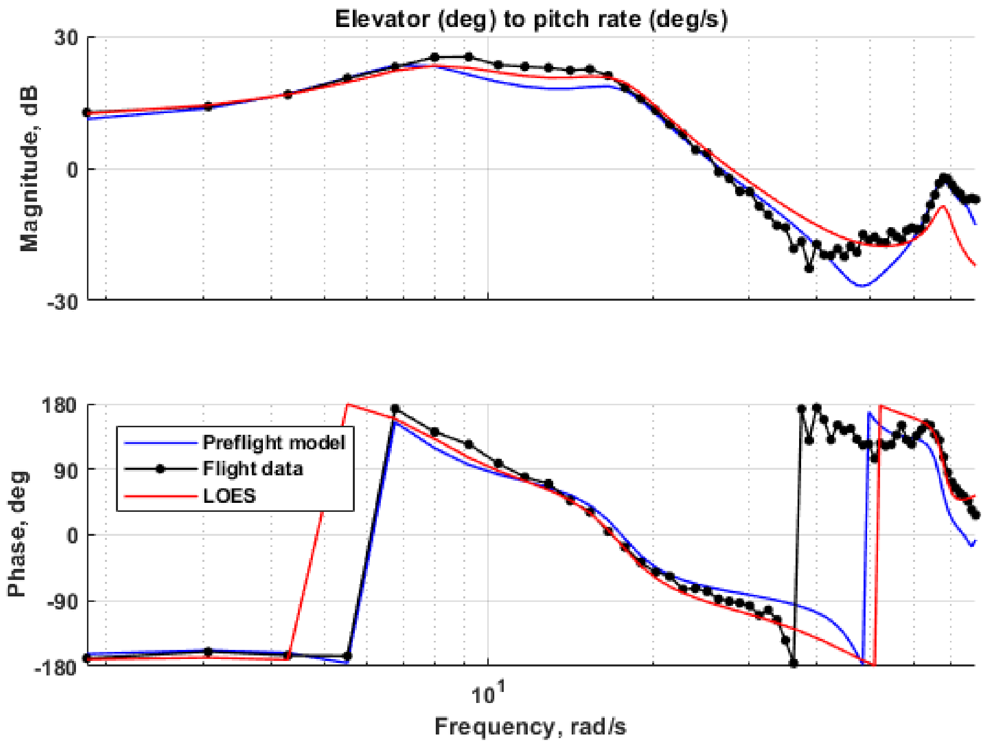
Real-time Monitoring and Post Flight Data Analysis

- Real-time Monitoring
  - Engineering disciplines in the GCS monitor for safety and data quality
  - Qualitatively watch for differences from preflight simulation predictions
  - Make real-time assessments of closed loop stability and damping from raps
  - Watch for actuator rate limiting and saturation which effectively open the loop and result in loss of control
  - Monitor limit-cycle oscillations (LCOs) that arise from actuator deadzones as an indicator of instability
- Post Flight Data Analyses
  - Controller loop margin assessments
  - Open loop modal frequency and damping determination
  - System identification and model validation



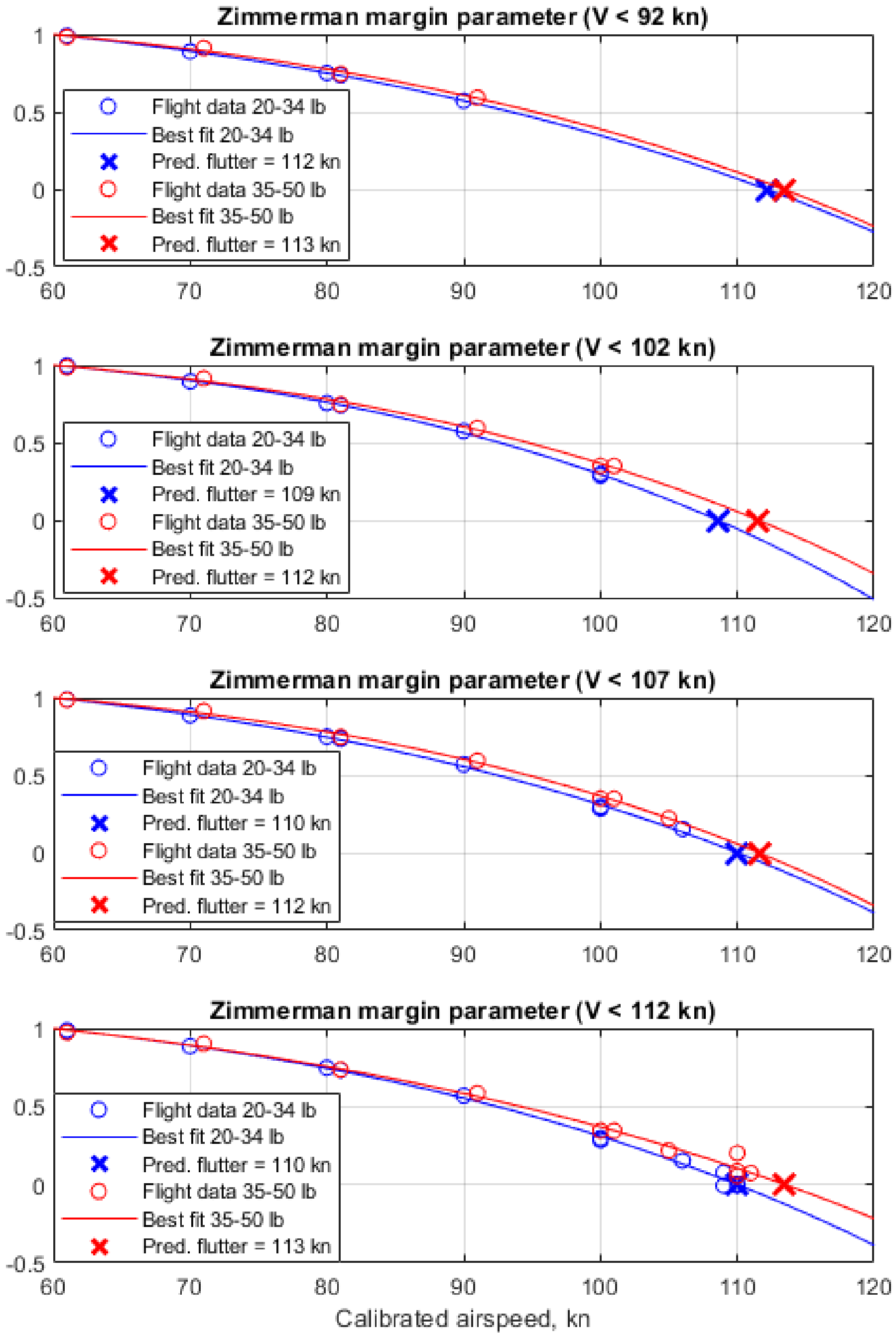
Frequency Reponses and LOES Models

- Frequency response reconstructions
  - Make use of known discrete input frequencies
  - Periodic so that difference cycles can be averaged
  - Reduces the effect of measurement noise and turbulence
  - Used extensively for determining margins and verifying model fidelity
  - Utilized both single loop and simultaneous multi-surface maneuvers
    - Cleanest reconstructions utilizing the single loop maneuvers used for determining margins
    - Reconstructions utilizing multi-surface maneuvers most useful for modal characterization at supercritical airspeeds
- Lower Order Equivalent Systems Fitting
  - Simultaneous fit of all surface to sensor transfer functions
  - 6^{th} order transfer functions with 3 complex poles: short-period, wing bending, and wing torsion
  - Fits done in both the time domain and the frequency domain
    - Time domain fits were the cleanest at subcritical airspeed and useful for control law tuning
    - Fits from multi-surface freq. reconstructions were used at supercritical airspeeds because they were less sensitive to the actuator deadzone dynamic interactions with the instability, but did not produce models useable for control law tuning



Zimmerman Flutter Margin Parameter

- Modal damping can change very rapidly for coupled flutter an many not be useful to predict flutter stability margin based on flight data
- Zimmerman flutter margin parameter
    - Based on the Routh's discriminate for the characteristic equation of the two modes coupling that generate the flutter instability
    - Quadratic with dynamic pressure at constant Mach number for quasi-steady aerodynamics with no structural damping
- Worked very well for X-56A predicting flutter speed with only a few flight data points

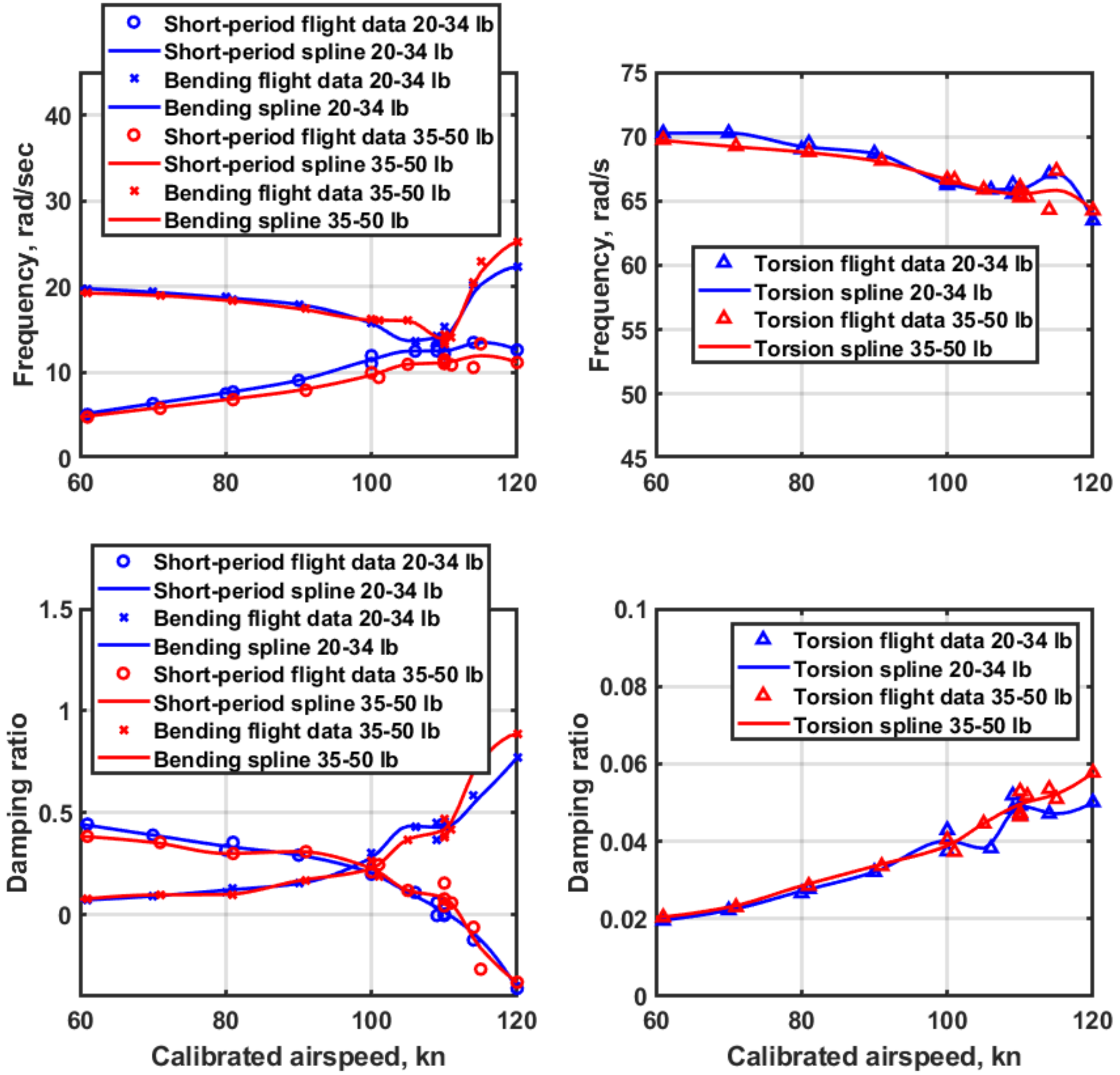


Modeling and Simulation

- Modeling Challenges
  - Tools for predicting flutter airspeed which are well established found to be insufficiently accurate for control system design and verification.
  - Modeling control effects the coupling characteristics of the modes contributing to flutter was a significant challenge especially for the X-56A flutter mechanism which involves rigid body modes
- Model development and evolution
  - High order linear models
    - Based on:
      - Finite element structural models correlated with ground-vibration-test data
      - Unsteady aerodynamics models based on potential flow tools
      - Steady aerodynamic models from wind-tunnel and stiff-wing flight-test data
    - Used for control law design and analysis prior to flexible-wing flights
    - Updated throughout the flight program based on flight data
    - Best representation of fully coupled dynamics up and away near flutter
    - Limitations
      - Difficult to use for piloted simulation testing or for analysis of fundamentally nonlinear flight regimes such as takeoff and landing.
  - Fully integrated piloted simulation
    - Mishaps revealed a need to account for flex modes during takeoff and landing
    - Non-linear piloted simulation modified to accurately simulate fully coupled dynamics
    - Used for developing operational procedures, special control law modes for takeoff and landing, and for pilot and GCS crew training
  - Flight data derived models
    - Linear transfer function models were derived directly from the flight-test data.
    - Used for validating control law designs and margins, and for identifying control law design changes between envelope expansion test points

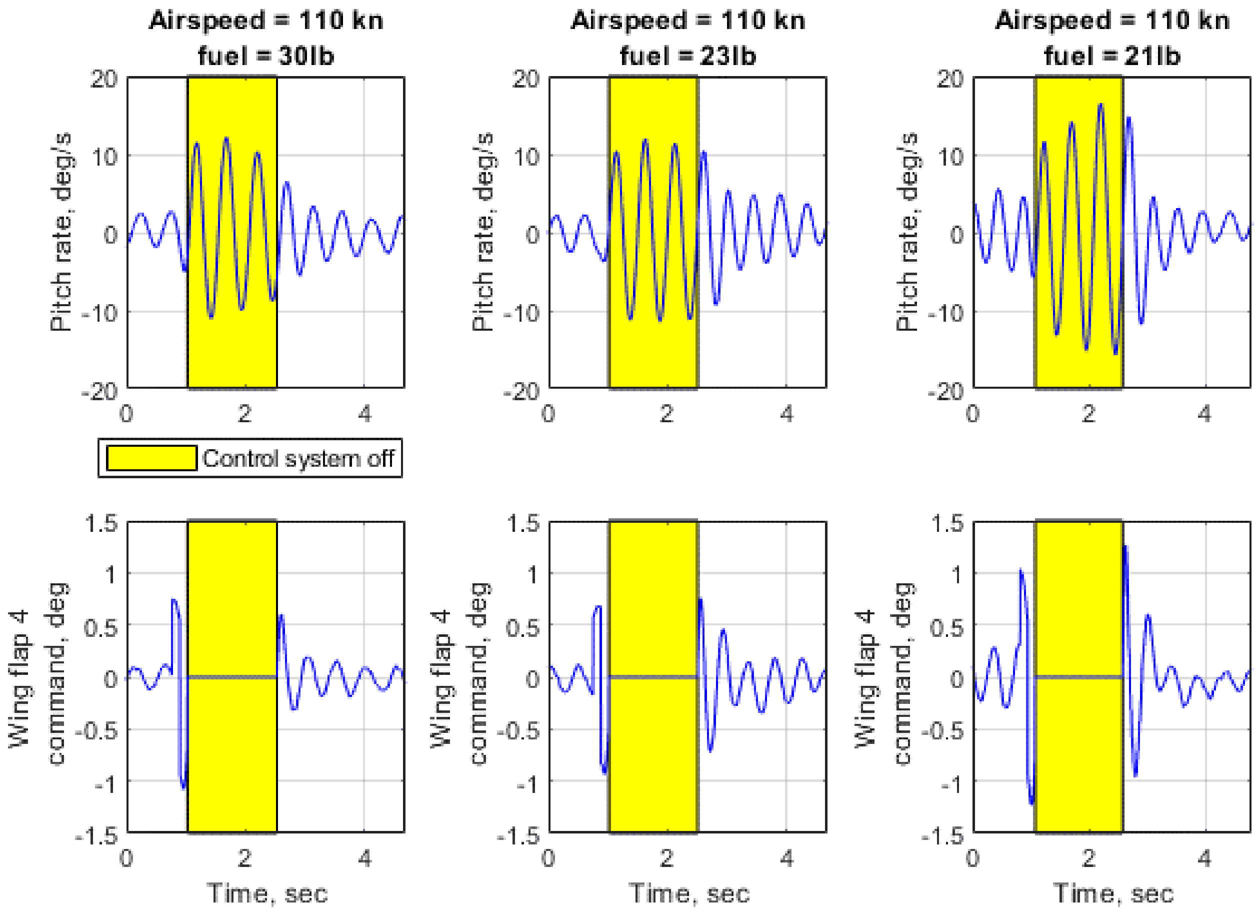
Results

- The flight envelope was expanded out to 120 kn, which was ~10 kn above the open-loop flutter instability at low fuel mass.
- Frequencies of the short-period and first wing bending modes converge at the flutter instability and then diverge again in the unstable region.
- At 120 kn, the torsional mode is still well separated from the bending mode, suggesting significant margin to the next predicted unstable flutter mechanism.



Results

- Open loop raps were used to verify the instability
  - Control system disengaged and a rap maneuver used to excite the frequencies of concern
  - After a set period of time the control system automatically re-engages and actively damps the mode
  - Only possible near neutral stability due to the explosive nature of the instability
- Plot shows that at 110 kn the mode was slightly stable at 30lbs of fuel, nearly neutrally stable at 23lbs of fuel, and unstable at 21 lbs of fuel



Flex wing flight test

Conclusions and Lessons Learned

- X-56A and flutter flight testing conclusions
  - Combined ground control station with pilot stations, control room, and simulation capabilities essential for this type of high-risk testing
  - Flight-test maneuvers utilizing automatic flight-test aids were a key enabler yielding higher quality data in a fraction of the flight-test time required by traditional techniques
  - The low-order equivalent system proved capable of capturing the complex flight dynamics to a very high degree and were useful for extracting modal information, and provided key insights used for control system design leading up to the flutter instability
  - Zimmerman flutter margin parameter yielded a very good estimate of the airspeed at which the flutter instability would occur, requiring very few flight-data points
- General lessons learned for testing of this nature with a UAV
  - Design the aircraft to be operationally robust even if it has a high-risk mission.
    - Neglecting seemingly mundane elements of the operation can lead to underestimating the risks associated with operating the aircraft. Takeoff and landing challenges greatly reduced the operational capacity of the X-56A aircraft, reducing the amount of research data that could be collected.
  - Flying unmanned aircraft situational awareness is often a significant challenge.
    - The X-56A ground control station was well laid out, ensuring that the pilot and engineering displays were clean and presented all of the key information.
    - Integrating the cockpit, simulation, and control room into a single asset allowed the team to train very effectively.
    - However, problems with the layout of the braking and throttle interfaces resulted in delays in decelerating the aircraft upon landing, which contributed to the first incident.
      - Subsequent flights utilized a conventional throttle layout and rudder pedals with toe brakes in order to eliminate modal confusion and improve the human machine interface for landing
  - Manage and communicate based on up-to-date risk assessments
    - First 2 incidents treated as full aircraft mishaps, slowed the progress for return to flight and delayed research
      - NASA leadership bought into the high-risk nature of the vehicle and granted a mishap exclusion letter acknowledging the risk posture
    - Taking too much operational risk can result in loss of the aircraft prior to achieving the goals of the project; however, being too risk-averse has the same outcome because resources are exhausted trying to drive risks below what is practical for the test mission.
    - Unmanned aircraft test operations need to thread the needle between taking too much or too little risk, and constantly adapt.

Questions?